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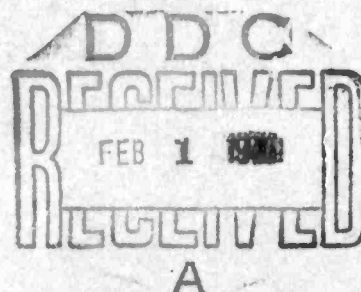
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THE EFFECT OF STRAIN RATE AND TEMPERATURE ON YIELDING IN STEELS

BY

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# BENET R&E LABORATORIES

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## THE EFFECT OF STRAIN RATE AND TEMPERATURE ON YIELDING IN STEELS

### ABSTRACT

The effect of elastic strain rates ranging from  $10^{-4}$  to  $10 \text{ sec}^{-1}$  and temperatures ranging from 200 K (-100 F) to 590 K (600 F) on the yield strength of several steels is reported. The steels utilized are a 1018 mild steel, 4340 steel, H-11 tool steel and 300 grade maraging steel.

The results are interpreted in terms of the Cottrell-Bilby yielding model based on release of dislocations from locking carbon atmospheres. The results for all of the materials except the maraging steel are consistent with this model if it is modified to account for re-locking of dislocations by migration of carbon atoms.

The maraging steel shows a constant strain rate sensitivity at a constant temperature, over the range of strain rates investigated. This rate sensitivity decreases with increasing temperature and at 590 K (600 F) a decreasing strength with increasing strain rate is found. This is attributed to stress aging effects.

### Cross Reference Data

Steels (mild, alloy, maraging)

Strain rate

Mechanical properties

Dislocation theory

Temperature effects

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# NOMENCLATURE

$t$	=	time, seconds
$U$	=	thermal activation energy
$k$	=	Boltzman's constant
$T$	=	absolute temperature, $^{\circ}\text{K}$
$\sigma$	=	stress, psi or ksi
$\sigma_0$	=	yield stress at $T = 0$
$n$	=	material constant
$N$	=	number of dislocations
$\gamma$	=	proportionality constant
$\epsilon$	=	strain
$\dot{\epsilon}$	=	strain rate $\text{second}^{-1}$
$E$	=	Young's modulus of elasticity
$D$	=	diffusion coefficient
$\alpha$	=	$1/nkT$
$c_{1,2,3,4}$	=	material constants

## INTRODUCTION

The effect of strain rate on yielding in high strength steels at room temperature has been reported by the author and T. E. Davidson in Ref. 1. In this paper it was shown that alloy steels generally exhibit two regions of strain rate sensitivity. These consist of a rate insensitive region at lower strain rates and a rate sensitive region at higher strain rates. The strain rate dividing the two regions is a function of the material composition and microstructure.

It was also found that the yield strength in the rate sensitive region is a power law function of strain rate and is consistent with a rate sensitive yielding model proposed by Campbell<sup>(2)</sup>. This model is based on the Cottrell-Bilby theory of yielding in iron-carbon alloys.

It is the purpose of this current work to extend the above results to elevated temperatures and to determine whether the proposed yielding model remains applicable at these temperatures.

Initial tests were conducted on several of the alloy steels used in the room temperature studies. These results indicate that the effect of increasing temperature is to increase the strain rate dividing the rate sensitive and insensitive regions. Therefore, the data which would be required to determine the effect of temperature on the rate sensitive region in these materials would have to be at strain rates well in excess of  $10 \text{ sec}^{-1}$ . This is beyond the capabilities of the currently available test system.

It was shown in Ref. 1 that the yielding behavior of alloy steels in the rate sensitive region is consistent with a yielding model based on mild steel. It is, therefore, hypothesized that if this model for mild steel could be extended to elevated temperatures, some information on the expected behavior of alloy steels could be inferred from this model. Obviously, any such inferred behavior would require eventual experimental verification.

Although a number of investigators have studied the effect of strain rate and temperature on the yielding of mild steel (see Ref. 1), most of these did not present enough data over a wide range of strain rates and temperatures to provide a valid check on the theory.

The most complete work in this area was the pioneering work of Manjoine<sup>(5)</sup>. However, he did not report any data at strain rates between 0.5 and 100 sec<sup>-1</sup> and reported yield strength data only at room temperatures and at 200°C (392°F). This work provides an excellent indication of the general trends of the relationships between yield strength, strain rate and temperature. However, it does not provide sufficient data to define the desired relationships precisely enough to verify the proposed theory. Therefore, an experimental program to define these relationships for a typical mild steel was undertaken. The material selected is a standard, commercial grade, 1018 steel in the annealed condition. The results of this program are compared with the previously proposed model from Ref. 1 and are found to be in agreement if a slight modification in the formulation of the model is made. This modification does not



affect the agreement of room temperature results noted in Ref. 1, or the basic assumptions used.

The above yielding model is then applied to the high strength alloys and the results compared with the experimental results obtained.

## PROCEDURE

### Apparatus

The testing system used to perform all of the tests reported herein is essentially the same systems described in Ref. 1 with the exception of the method of strain measurement. A special extensometer utilizing a "Kaman Nuclear" variable impedance type, displacement transducer was developed for the elevated temperature tests. This is shown in Fig. 1 and consists of a pair of stainless steel rods attached to the end of the lower loading bar into which the specimen is threaded. The displacement transducer is mounted on a bracket attached to the end of the upper loading bar and is initially in contact with the end of one of the stainless steel rods. The output of the transducer is proportional to the gap between the end of the rod and the transducer and thus is a measure of the relative displacement of the ends of the loading bars. This displacement is not a precise measure of the specimen strain due to elastic distortions of the threads and specimen end effects. However, accurate strain data for a specific material at room temperature can be obtained by calibrating the transducer output with a strain gage on the specimen for both elastic and plastic strains. At elevated temperatures some error in this calibration results from temperature

gradients which produce non-uniform variations in material properties. Since, for the purposes of this investigation, very accurate specimen strain data is not required, this error is considered negligible.

The load on the specimen is measured by strain gages mounted on the upper loading bar. For the high temperature tests these gages were BLH type HT-412-4A-S6 gages applied by the "Rokide" flame spraying process. This load measuring system is calibrated statically at room temperature to an accuracy of  $\pm 1\%$ . At elevated temperatures there will be a slight error in this calibration due to changes in elastic modulus of the loading bar and in the gage factor of the strain gages. The temperature of the gaged portion of the loading bar was found to not exceed 350°F for the maximum test temperature reported. This would result in an error of less than 5% and the error would be constant at any one test temperature so that it would not affect any indicated strain rate sensitivity.

The load cell and displacement transducer output are connected to both a light beam type oscillograph having a frequency response of DC to 5000 Hz and an X-Y storage type oscilloscope. The oscillograph provides both load-time and displacement-time curves while the oscilloscope provides a load-displacement curve directly.

Heating of the specimens is accomplished by a conventional split tubular, electrical resistance furnace with a heated zone 3 inches in diameter by 5 inches long. A single zone type of control is used and was found to produce an essentially constant specimen temperature over

most of the reduced section. The temperature is measured by a chromel-alumel thermocouple welded directly to the specimen and connected to a standard temperature recorder-controller. The specimens are heated to the test temperature at a heating rate of about 15°F per minute and held at test temperature for about 5 minutes before testing. For the low temperature tests the specimens are immersed in a bath containing a mixture of dry ice and alcohol.

The only results reported are yield strength and elastic strain rate in order to avoid errors due to adiabatic heating and variations in strain rate in the plastic region. Although some plastic flow occurs prior to the .2% offset yield, any resulting temperature and microstructural changes would be negligible. The time average strain rate up to this point is essentially the same as the elastic strain rate.

#### Specimens and Materials

The specimens utilized were standard ASTM round tensile specimens having a .505 inch diameter and threaded ends. The alloy steels used were 4340 steel, H-11 high chromium tool steel and 18% Ni 300 grade maraging steel. The chemical compositions and heat treatments are given in Ref. 1 and will not be repeated here since they are essentially standard. The 4340 steel was heat treated to produce a fine grained, martensitic structure and was tempered at 1025°F.

The mild steel used was a commercial grade 1018 steel purchased in the form of 1 inch diameter bar stock in the cold rolled condition.

The bars were cut into 5 inch lengths, annealed at 1550°F for 1 hour and furnace cooled. The bars were then machined into test specimens. The chemical composition is as follows: C - 0.15 w/o, Mn - 0.65 w/o, N<sub>2</sub> - 13 ppm, O<sub>2</sub> - 205 ppm.

#### THEORY

A relationship for the effect of strain rate on the yield strength of plain iron-carbon alloys has been developed by Campbell<sup>(2)</sup> predicated on a theory of yielding originally proposed by Cottrell and Bilby<sup>(3)</sup>. This theory is based on the assumption that yielding will occur when a sufficient number of dislocations (N<sub>c</sub>) are released from their locking carbon atmospheres. Cottrell and Bilby give the mean time for the release of a dislocation (t<sub>0</sub>) as:

$$t_0 \propto \exp (U/kT) \quad \dots \dots \dots (1)$$

where U is the required thermal activation energy and is a function of the applied stress.

Yokobori<sup>(4)</sup> has suggested that this activation energy can be approximated by:

$$U = - \frac{1}{n} \ln \frac{\sigma}{\sigma_0} \quad \dots \dots \dots (2)$$

Based on the relationships of equations (1) and (2), Campbell obtained the following relationship for the yield strength in a constant strain rate test.

$$\sigma_y = \sigma_0 \left[ \left( \frac{1 + nkT}{nkT} \right) \frac{\gamma N_c E}{\sigma_0} \dot{\epsilon} \right]^{\frac{nkT}{1 + nkT}} \quad \dots (3)$$

The complete derivation of equation (3) is given in both Refs. 1 and 2.

For a constant temperature equation (3) can be rewritten as

$$\sigma_y = \sigma_0 \left( \frac{c_3}{c_4} \dot{\epsilon} \right)^{c_4} \dots \dots \dots (4)$$

$$\text{where } c_4 = \frac{nkT}{1 + nkT}$$

and  $c_3$  = a material constant

If the slope of the logarithmic yield stress-strain rate curve for a given material at a constant temperature is known, the value of  $c_4$  for that material can be calculated. From this and the value of yield strength at a given strain rate the value of  $c_3$  can be calculated from equation (3). The variation of yield strength with temperature at a constant strain rate in the rate sensitive region can then be determined, assuming no structural changes or change in yielding mechanism.

Using the room temperature data for the 1018 steel shown in Fig. 5 to determine  $n$  for this material, it was found that equation (3) does not predict the relationship between yield strength and temperature at any strain rate considered. This equation predicts a much more rapid decrease in yield strength with increasing temperature than is found experimentally.

This indicates that there is some other mechanism acting which has the tendency to increase the yield strength as the temperature is increased. It has been suggested by Cottrell and Bilby<sup>(3)</sup> and by Manjoine<sup>(5)</sup> that the yielding of iron-carbon alloys is also effected by strain aging. This phenomenon is believed to result from the relocking of free dislocations by migration of carbon atoms.

Cottrell and Bilby<sup>(3)</sup> showed that the number of carbon atoms which will arrive at a given point in some given time is

$$N \propto \left(\frac{D}{kT}\right)^{\frac{2}{3}} \int_0^t \frac{dt}{t^{1/3}}$$

Analysis of the number of dislocations that will be re-locked during the course of a rising load test of the type in question is highly complex. Both the number of free dislocations and the velocity of these dislocations is constantly changing. Therefore, a detailed analysis of this dislocation re-locking will not be attempted. It will simply be assumed that the number of dislocations released and not re-locked can be obtained by multiplying the total number released by a function of temperature,  $f(T)$ . The form of this function will be determined experimentally.

As in the original derivation, the total number of dislocations released in any time will be:

$$\gamma N_t = \int_0^t \exp\left(-\frac{U}{kT}\right) dt \quad \dots (5)$$

The number released and not re-locked will be:

$$\gamma N_c = \int_0^t \exp\left(-\frac{U}{kT}\right) f(T) dt \quad \dots (6)$$

Substituting the expression for  $U$  from equation (2) and assuming that yielding will occur when the net number of released dislocations reaches some critical value,  $N_c$ , yields

$$\gamma N_c = \int_0^{t_c} \exp \left( \frac{1}{nkT} \ln \frac{\sigma}{\sigma_0} \right) f(T) dt$$

or

$$\gamma N_c = \int_0^{t_c} \left( \frac{\sigma}{\sigma_0} \right)^{\frac{1}{nkT}} f(T) dt \quad \dots (7)$$

For a constant strain rate test, in the elastic range

$$\sigma = E \dot{\epsilon} t \quad \dots (8)$$

Substituting equation (8) into equation (7) and integrating yields

$$t_c = \left[ \left( \frac{\sigma_0}{E \dot{\epsilon}} \right) (\alpha + 1) \frac{\gamma N_c}{f(T)} \right]^{\frac{1}{\alpha + 1}} \quad \dots (9)$$

where  $\alpha = \frac{1}{nkT}$ .

At yield  $\sigma = \sigma_y$  and  $t = t_c$ . Therefore, equation (8) becomes

$$t_c = \frac{\sigma_y}{E \dot{\epsilon}} \quad \dots (10)$$

Substituting equation (10) into equation (9) and simplifying yields

$$\sigma_y = \sigma_0 \left[ (\alpha + 1) \frac{\gamma N_c E \dot{\epsilon}}{\sigma_0} f(T) \right]^{\frac{1}{\alpha + 1}} \quad \dots (11)$$

or

$$\sigma_y = \sigma_0 \left[ \left( \frac{1 + nkT}{nkT} \right) \frac{\gamma N_c E \dot{\epsilon}}{\sigma_0} f(T) \right]^{\frac{nkT}{1 + nkT}} \quad \dots (12)$$

## RESULTS AND DISCUSSION

The results for the 4340 and H-11 steels at 600°F are shown in Figures 2 and 3 along with the room temperature results from Ref. 1. In both cases the increase in temperature eliminates any strain rate

sensitivity that was seen at room temperature within the range of strain rate shown. The results for the H-11 steel show that the elevated temperature has increased the strain rate dividing the sensitive and insensitive regions to a value exceeding  $3.0 \text{ sec}^{-1}$ . The verification of this assumption would require elevated temperature tests at strain rates in the region of 10 to  $100 \text{ sec}^{-1}$  which involve considerable experimental difficulty. In order to avoid this difficulty, and for other reasons discussed in the introduction, a detailed study of the effect of temperature and strain rate on yielding of a mild steel was conducted. The material selected for this study was a standard 1018 mild steel in the annealed condition. Since the yielding model under consideration is related to the initial yielding of the material, the quantity studied experimentally is the upper yield point stress. Unfortunately, this quantity is generally subject to considerable data scatter since it can be effected by such factors as specimen alignment and axiality of load. However, other variables which could be used were found to be no more reliable. For example, it is generally recognized that the lower yield point can be affected by the relative "softness" of the testing machine. Since the test system utilized is an inherently "soft" machine with the degree of "softness" varying with both strain rate and temperature, the lower yield point was not considered a reliable test result. The value of stress at some small plastic strain value, such as 2%, is also often used. However, due to the steepness of the stress-strain curve in this region, unavoidable slight errors in strain measurement result in significant stress errors.



In view of these complications the upper yield point results are the only data reported herein.

All of the results of the 1018 mild steel are shown in Figures 4-8 as the natural logarithm of the upper yield strength in ksi versus the logarithm of the elastic strain rate at various temperatures. Each data point represents a single test specimen. The results reported by Manjoine<sup>(3)</sup> are also shown in Figures 5 and 7. The points shown at a strain rate of  $10 \text{ sec}^{-1}$  are obtained by interpolating his data from higher and lower strain rates. Considering the variability generally found in this type of material, the agreement is reasonable.

The results shown in Figures 4-7 were used to determine the functional relationship for  $f(T)$  in equation (12). At a constant strain rate equation (12) gives  $\sigma_y$  as a function of  $T$  only. By plotting experimental values of  $\sigma_y$  versus  $T$  at various strain rates, it was found that a function of  $T$  having the form of  $B(T)^A$ , where  $A$  and  $B$  are material constants, resulted in good agreement with the form of the  $\sigma_y$  versus  $T$  curves in the rate sensitive regions.

By defining two new constants

$$\begin{aligned} c_1 &= \frac{\gamma N_c}{B} \\ c_2 &= -A \end{aligned}$$

equation (12) becomes

$$\sigma_y = \sigma_0 \left[ \left( \frac{1 + nkT}{nkT} \right) \frac{\dot{\epsilon} E}{\sigma_0} c_1 T^{c_2} \right]^{\frac{nkT}{1 + nkT}} \dots (13)$$

The constants  $c_1$  and  $c_2$  may be determined from the data shown in Figures 4-7. Since equation (12) applies only in the rate sensitive

region experimental values of  $\sigma_y$  were determined at a strain rate of  $1.0 \text{ sec}^{-1}$  and at temperatures of 200, 300, 394 and  $477^\circ\text{K}$ . The value of  $n$  was determined from the slope of the room temperature ( $300^\circ\text{K}$ ) data and was found to be  $2.575 \times 10^{-4}$ . Although the elastic modulus varies slightly with temperature, it is assumed to be constant over the temperature range considered and equal to  $30 \times 10^6 \text{ psi}$ . A value of  $\sigma_0 = 310,000 \text{ psi}$ , as suggested by Russell, Wood and Clark<sup>(6)</sup>, is used. The values of  $c_1$  and  $c_2$  are then determined by substituting the above constants into equation (13) and obtaining a best fit curve of  $\sigma_y$  versus  $T$  for  $\dot{\epsilon} = 1.0$ . This was accomplished on a digital computer using a least squares curve fitting technique. The values thus obtained are:

$$c_1 = .340 \times 10^{-31}$$

$$c_2 = 7.477$$

These were substituted into equation (13) and the yield strength-strain rate curves calculated for the various test temperatures. These are shown as the solid lines in Figures 4-8. The agreement is quite good considering the inherent variability of the test data.

In order to investigate the applicability of the proposed theory to high strength alloy steels, the results for the H-11 steel from Ref. 1 are re-plotted on a log-log basis in Figure 9. A few additional tests were conducted at  $-100^\circ\text{F}$  ( $200^\circ\text{K}$ ) and these results are also shown in Figure 9. From the slope of the room temperature results, a

value of  $nk = 0.708 \times 10^{-4}$  is determined for this material. The value of  $\sigma_0$  for this material is estimated to be 400 ksi by extrapolation of data published by Campbell and Rice<sup>(7)</sup> and a value of  $E = 30 \times 10^6$  is assumed for all temperatures. By substituting the above constants, along with the yield strengths at a strain rate of  $1.0 \text{ sec}^{-1}$  and at  $300^\circ\text{K}$  and  $200^\circ\text{K}$  from Figure 9, into equation (13) the values of  $c_1$  and  $c_2$  for this material can be determined. These were found to be:

$$\ln c_1 = -72.8$$

$$c_2 = 7.63$$

The yield strength-strain rate curves calculated from equation (13) using the above constants are shown in Figure 9 for the rate sensitive region. The agreement is good as would be expected since the experimental data were used to determine the constants in the equation. Two points of agreement which are not a result of this fact are worth noting. The slope of the rate sensitive region of the curve at  $200^\circ\text{K}$  agrees very well with the data. The theory also predicts that at  $590^\circ\text{K}$  the strain rate dividing the rate sensitive and insensitive regions is greater than the  $10 \text{ sec}^{-1}$  which is consistent with the data.

The results for the 18% nickel maraging steel are shown in Figure 10. This material shows a different type of response to strain rate and temperature than the other materials considered in this paper.

This would be expected since the controlling strengthening mechanisms in this material are quite different from those of the other materials.

A linear relationship between logarithmic strain rate and temperature exists at all temperatures considered. The effect of increasing temperature is to decrease the slope of this curve. At 600°F a decrease in yield strength with increasing strain rate is found. This is believed to be due to the fact that dynamic stress aging is occurring during the low strain rate tests at this temperature. This is indicated by the fact that the low strain rate yield strength at 600°F is essentially the same as that at 400°F. At the higher strain rates there is not sufficient time for this dynamic stress aging to occur and thus a decreasing yield strength is found.

The above conclusions seem to be consistent with the results of Harrington<sup>(8)</sup> and Wright<sup>(9)</sup> who both demonstrated significant stress aging effects in maraging steels. No direct comparisons can be made, however, since the aging times used by these investigators were considerably longer than those applicable to the "static" tests reported in this paper.

#### CONCLUSIONS

1. The effect of increasing temperature on the strain rate sensitivity of mild steel and ordinary quenched and tempered alloy steels is to increase the slope of the yield strength-strain rate curve in the rate sensitive region and to shift the strain rate dividing the rate sensitive and insensitive regions to a higher strain rate.

2. The yield strength of such steels, in the rate sensitive region, is given by an equation based on the Cottrell-Bilby theory of yielding. This theory is predicated on dislocation breakaway from locking carbon atmospheres and is empirically modified to account for re-locking of dislocations by migration of carbon atoms.

3. The strain rate sensitivity of 300 grade maraging steel decreases with increasing temperature. At 590°K (600°F) this material shows a decreasing strength with increasing strain rate which is attributed to dynamic stress aging during the low strain rate tests.

#### ACKNOWLEDGMENTS

The author acknowledges the guidance and helpful suggestions of T. E. Davidson and the assistance of W. M. Yaiser and R. R. Fuczak in conducting the experiments reported herein.

#### ADDENDUM

Subsequent to the submission of the manuscript of this paper, the author became aware of a recent paper by Campbell and Ferguson<sup>(10)</sup>. They reported the effects of strain rate and temperature on the shear strength of mild steel over a very wide range of strain rates. Since they did not report upper yield strength data, a direct comparison is not possible. However, the trends of their results are very similar to those reported in this paper.

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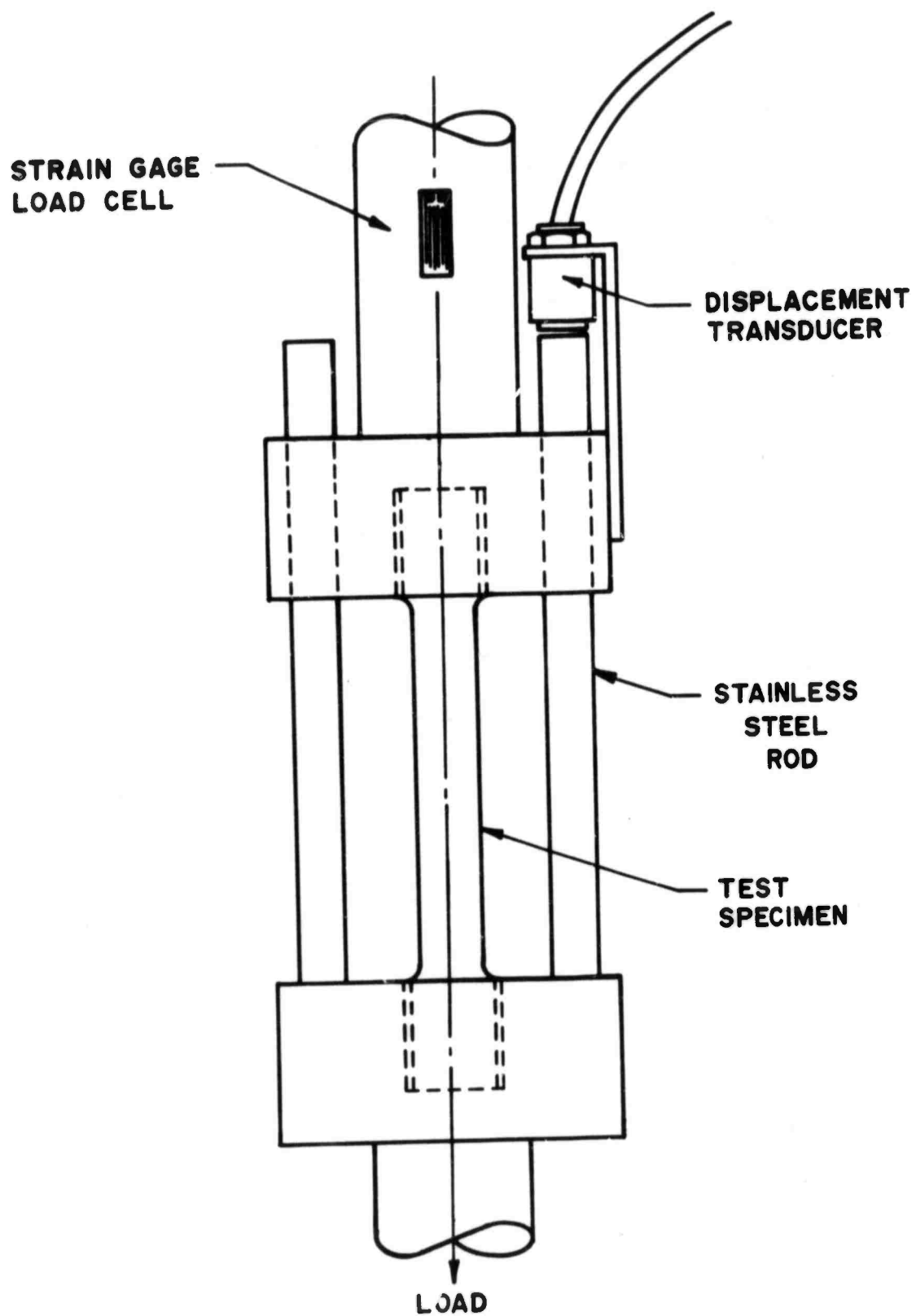


Figure 1. Load and Displacement Measuring System



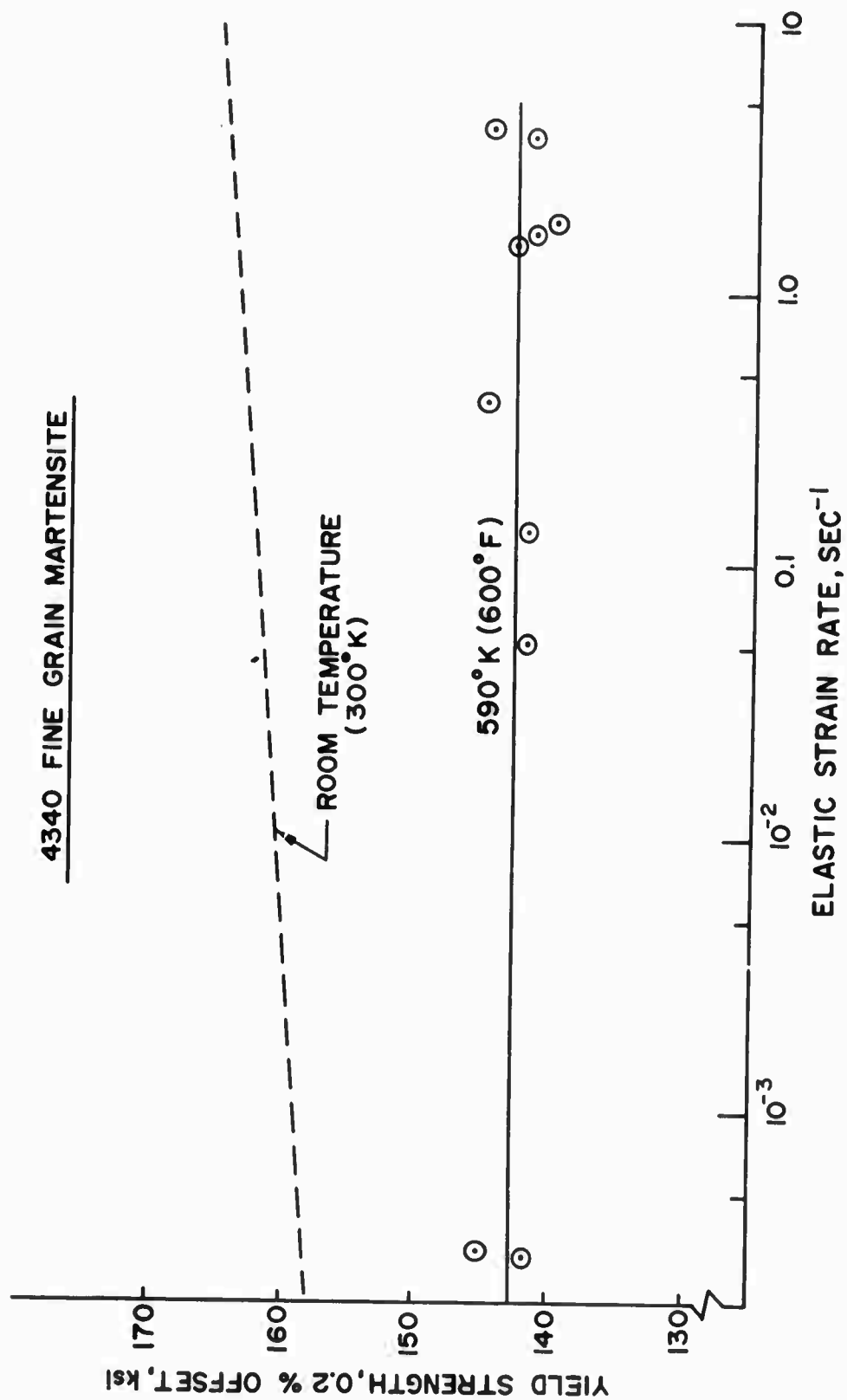


Figure 2. Yield Stress vs. Elastic Strain Rate for 4340 Fine Grain Martensite

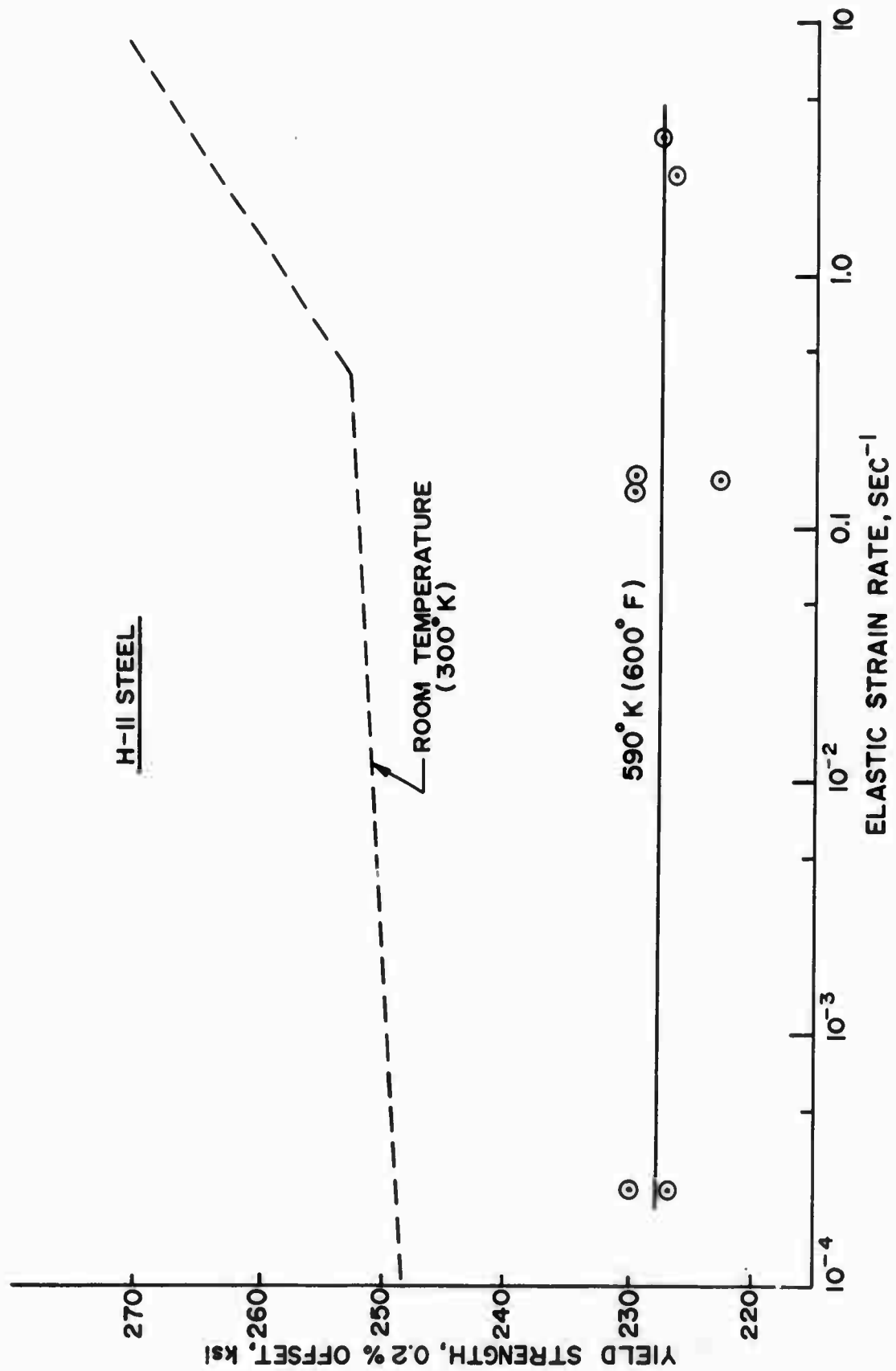


Figure 3. Yield Stress vs. Elastic Strain Rate for Type H-II Steel

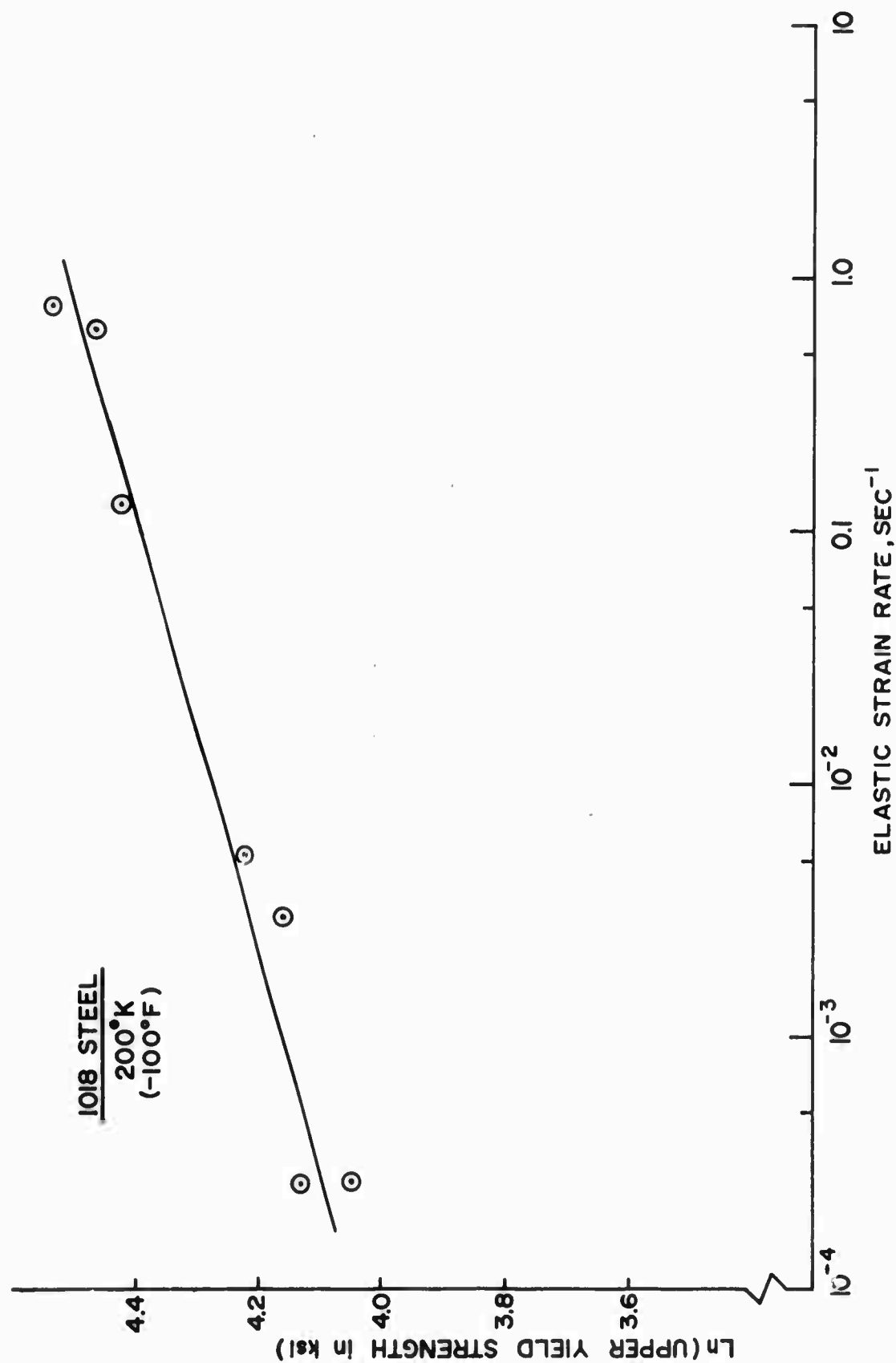


Figure 4. Logarithm of Upper Yield Stress vs. Elastic Strain Rate for 1018 Steel at 200°K



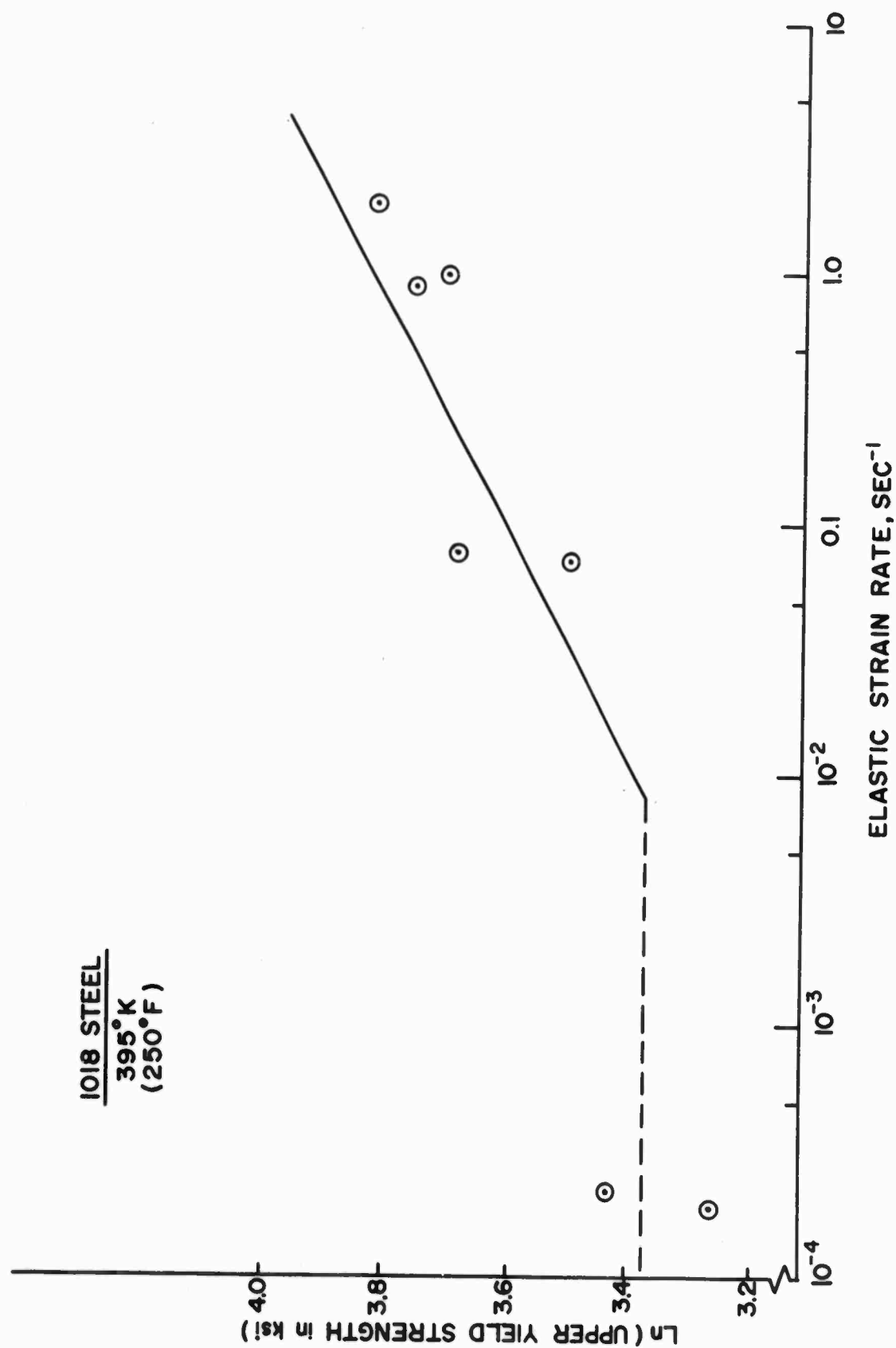


Figure 6. Logarithm of Upper Yield Stress vs. Elastic Strain Rate for 1018 Steel at 395°K

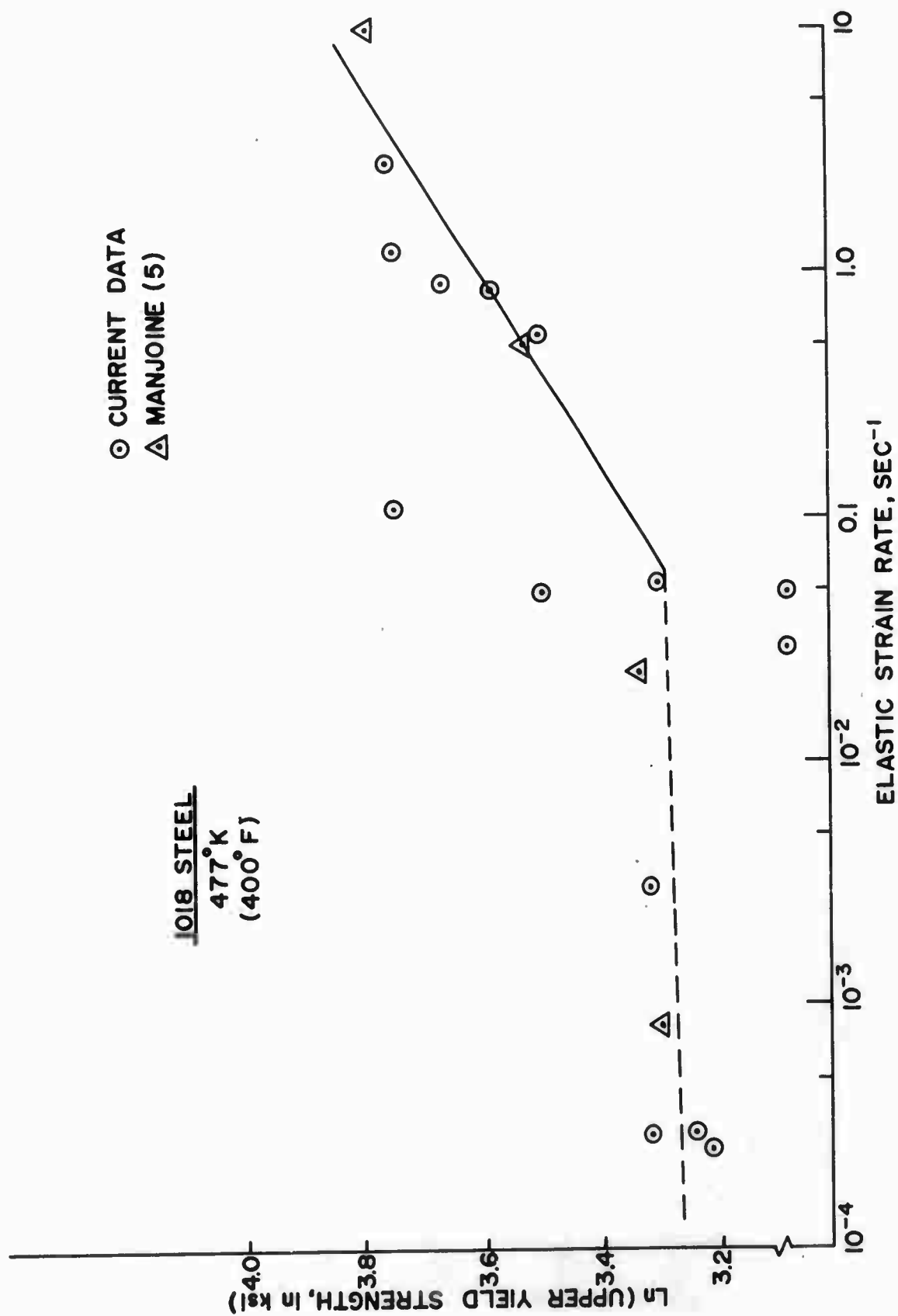


Figure 7. Logarithm of Upper Yield Stress vs. Elastic Strain Rate for 1018 Steel at 477°K

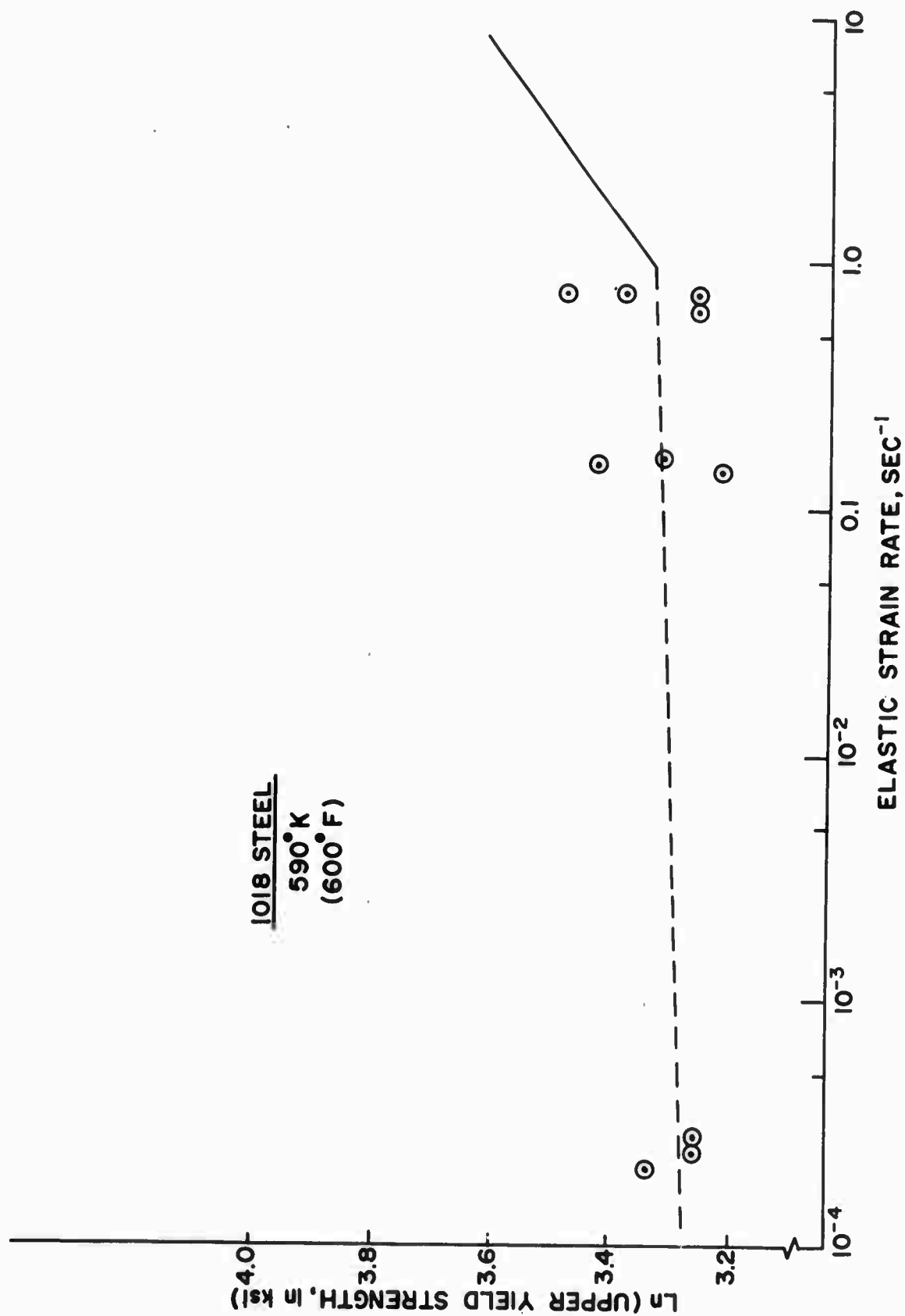


Figure 8. Logarithm of Upper Yield Stress vs. Elastic Strain Rate for 1018 Steel at 590°K

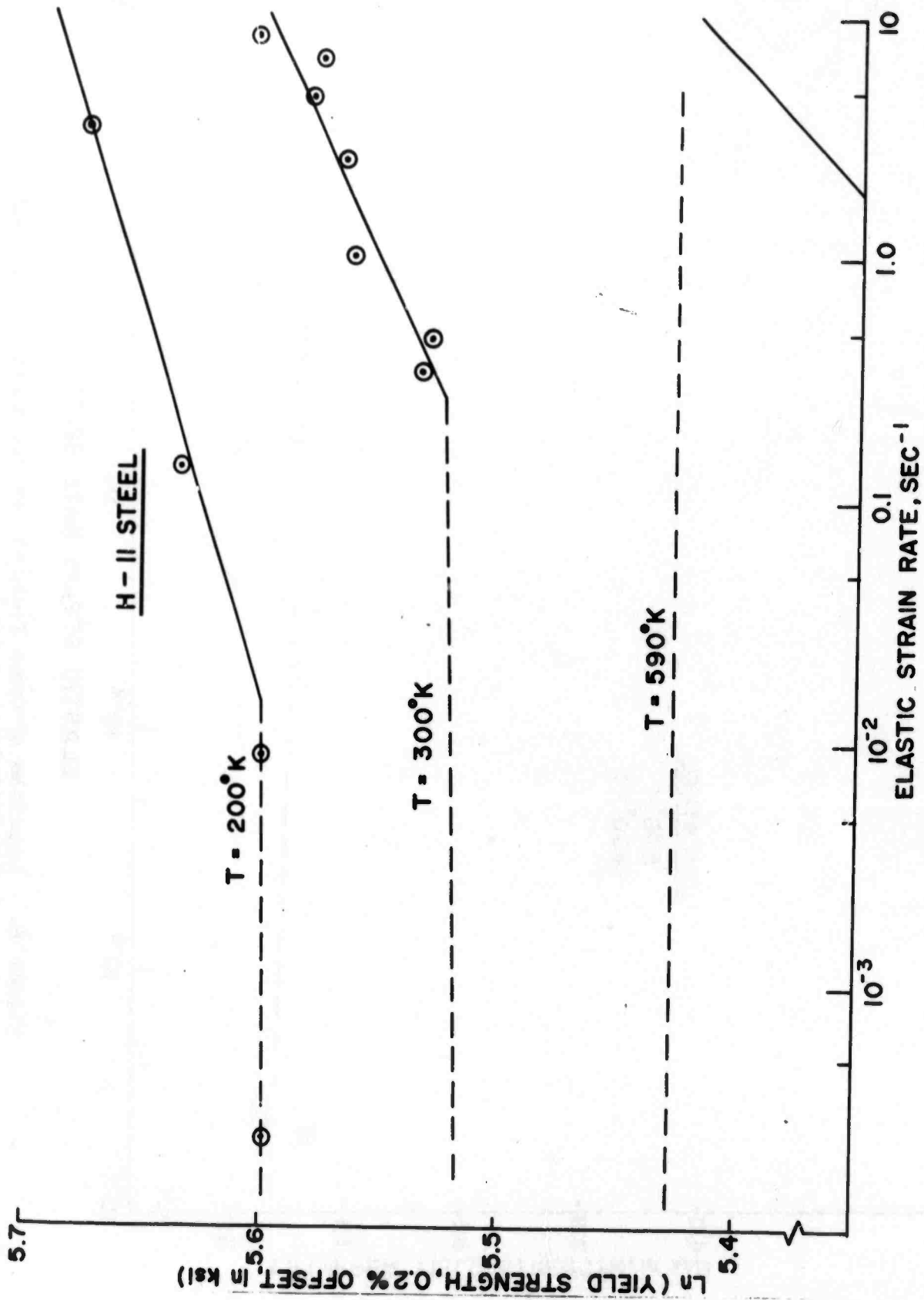


Figure 9. Logarithm of Yield Stress vs. Elastic Strain Rate for Type H-11 Steel



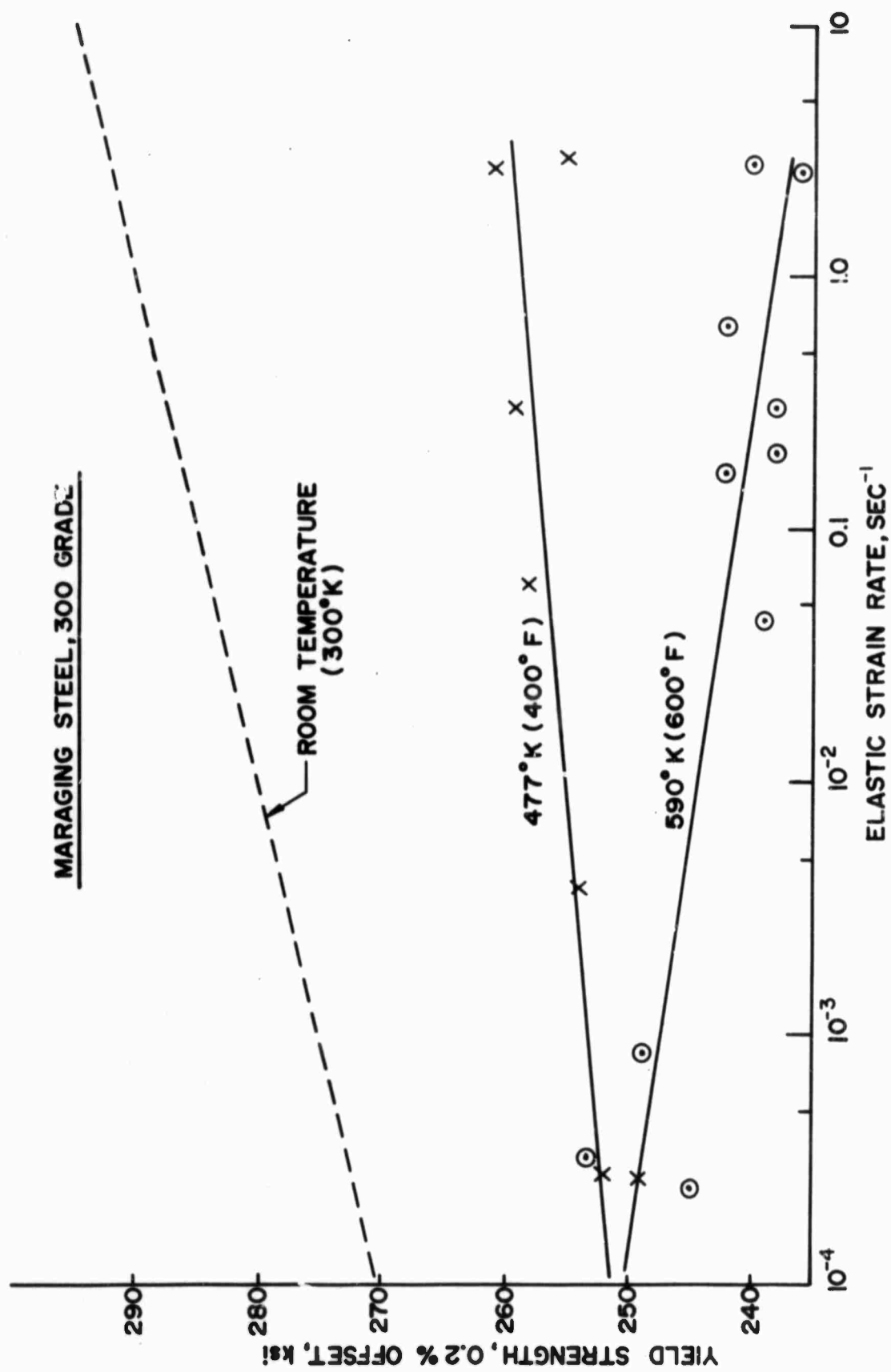


Figure 10. Yield Stress vs. Elastic Strain Rate for Maraging 300 Steel

AD Benet Laboratories, Watervliet Arsenal, Watervliet, N.Y.	Accession No.	Steel (mild, alloy, maraging)
THE EFFECT OF STRAIN RATE AND TEMPERATURE ON YIELDING IN STEELS by David P. Kendall		Strain rate
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